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AUTOMOBILE GAS TURBINE ENGINE STUDY FOR THE ENVIRONMENTAL PROTECTION AGENCY

AiResearch Manufacturing Company of Arizona

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SUMMARY REPORT

AUTOMOBILE GAS TURBINE ENGINE STUDY

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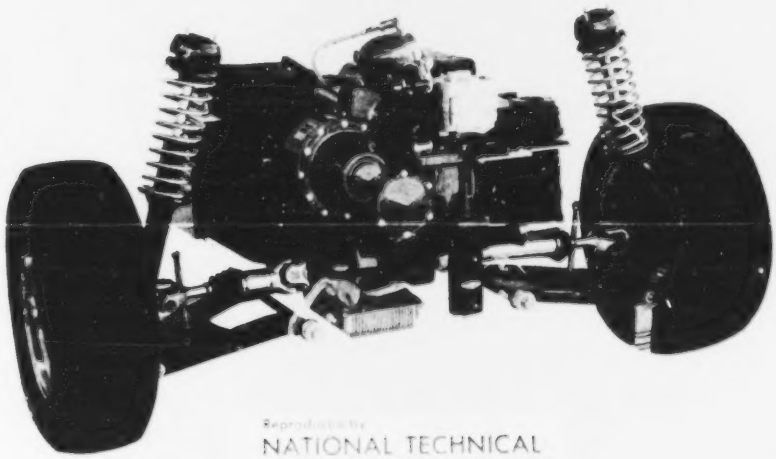

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SEPTEMBER 15, 1972

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

MP-34987

Note

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15. Supplementary Notes

16. Abstracts The aim was to determine the optimum gas turbine powerplant system for a standard six-passenger automobile. The major goals for the gas turbine automobile are (1) it should meet the 1976 Federal Emissions Standards and (2) it should be similar to, or better than, the present automobile with respect to: acceleration; performance; initial consumer cost; fuel economy; and maintenance and repair costs. Through proper design, a gas turbine engine/transmission system can be mass-produced at an estimated cost comparable to a 1970 spark ignition (SI) system. The optimum gas turbine (GT) system has a lower computed average fuel consumption than the 1970 SI system and the GT system vehicle acceleration response would equal or exceed the SI system. This study is a limiting case since the engine cycles were not penalized for low-emission combustor designs, because the penalty, if any, has not yet been quantitatively determined. Federal driving cycle emissions were computed for the three candidate systems using data from existing AiResearch engines and analytical techniques. It was found that all of the engines met the CO and UHC requirements with margin, but that none of these conventional combustors met the NOx requirement. Schematics of the systems are presented. The design point characteristics are tabulated. Tables are also presented and discussed of acceleration performance, fuel economy, and costs to the manufacturer and consumer, and of repair and maintenance, and ownership cost. Other figures of the recommended engine system, a mock-up of the engine-transmission system, the demonstration program logic chart, schedule, and milestones are also discussed.

17. Key Words and Document Analysis. 17a. Descriptors

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Economics
Maintenance
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Carbon monoxide
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SUMMARY REPORT

AUTOMOBILE GAS TURBINE ENGINE STUDY

for the ENVIRONMENTAL PROTECTION AGENCY

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AT-6100, REV. 1 SEPTEMBER 15, 1972

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

SUMMARY REPORT

AUTOMOBILE GAS TURBINE ENGINE STUDY FOR THE ENVIRONMENTAL PROTECTION AGENCY

THE STUDY PROGRAM OBJECTIVE WAS TO DETERMINE THE OPTIMUM GAS TURBINE POWERPLANT SYSTEM FOR A STANDARD SIX-PASSENGER AUTOMOBILE. THE MAJOR GOALS FOR THE GAS TURBINE AUTOMOBILE ARE (1) IT SHOULD MEET THE 1976 FEDERAL EMISSIONS STANDARDS AND (2) IT SHOULD BE SIMILAR TO, OR BETTER THAN, THE PRESENT AUTOMOBILE WITH RESPECT TO:

- ACCELERATION
- PERFORMANCE
- INITIAL CONSUMER COST
- FUEL ECONOMY
- MAINTENANCE AND REPAIR COSTS.

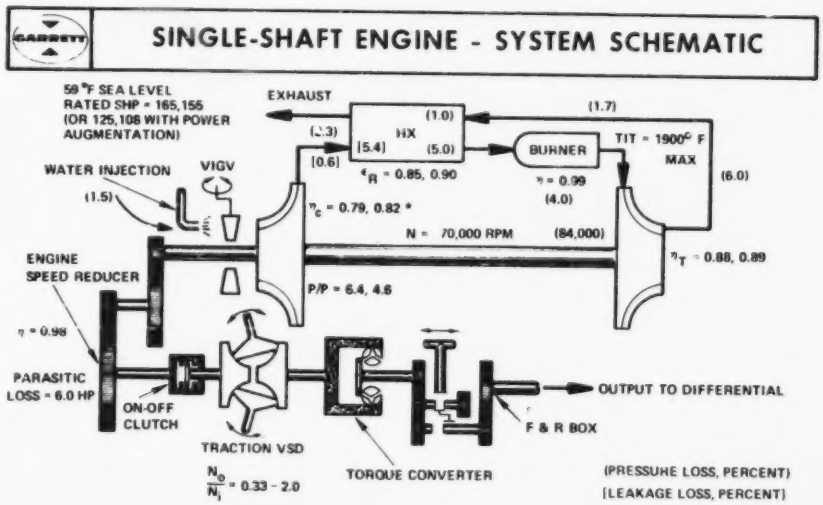
DURING THIS STUDY, IT WAS DETERMINED THAT, THROUGH PROPER DESIGN, A GAS TURBINE ENGINE/TRANSMISSION SYSTEM CAN BE MASS-PRODUCED AT AN ESTIMATED COST COMPARABLE TO A 1970 SPARK IGNITION (SI) SYSTEM.* IT WAS ALSO FOUND THAT THE OPTIMUM GAS TURBINE (GT) SYSTEM HAS A LOWER COMPUTED AVERAGE FUEL CONSUMPTION THAN THE 1970 SI SYSTEM AND THE GT SYSTEM VEHICLE ACCELERATION RESPONSE WOULD EQUAL OR EXCEED THE SI SYSTEM. THIS STUDY IS A LIMITING CASE SINCE THE ENGINE CYCLES WERE NOT PENALIZED FOR LOW-EMISSION COMBUSTOR DESIGNS, BECAUSE THE PENALTY, IF ANY, HAS NOT YET BEEN QUANTITATIVELY DETERMINED. FEDERAL DRIVING CYCLE EMISSIONS WERE COMPUTED FOR THE THREE CANDIDATE SYSTEMS USING DATA FROM EXISTING AIRESEARCH ENGINES AND ANALYTICAL TECHNIQUES. IT WAS FOUND THAT ALL OF THE ENGINES MET THE CO AND UHC REQUIREMENTS WITH MARGIN, BUT THAT NONE OF THESE CONVENTIONAL COMBUSTORS MET THE NO_X REQUIREMENT.

*DEFINED FOR THE PURPOSES OF THIS STUDY AS A STANDARD 1970 SPARK-IGNITION ENGINE WITHOUT ADDITIONAL EMISSION CONTROL DEVICES.

THE OPTIMUM GT SYSTEM WAS FOUND TO BE A RELATIVELY LOW-PRESSURE RATIO, SINGLE-SHAFT ENGINE WITH HIGH HEAT RECOVERY EFFECTIVENESS COUPLED TO AN INFINITELY VARIABLE SPEED RATIO TRACTION-TYPE TRANSMISSION. IN THE SEARCH TO FIND THE OPTIMUM GT SYSTEM, A LARGE NUMBER OF POTENTIAL ENGINE CYCLES, INCLUDING SINGLE-SHAFT, FREE-TURBINE, AND MULTI-SPOOL CONFIGURATIONS, WERE CONSIDERED. THE STUDY ALSO INCLUDED CONSIDERATION OF SINGLE- AND MULTI-STAGE COMPRESSORS AND TURBINES WITH BOTH AXIAL- AND RADIAL-FLOW COMPONENTS, COOLED AND UNCOOLED TURBINES, FIXED AND VARIABLE GEOMETRY, AND SIMPLE- AND REGENERATED-CYCLES. ENGINE PRESSURE RATIOS OF 4 TO 16, AND TURBINE INLET TEMPERATURES OF 1600° TO 2200°F WERE CONSIDERED.

FROM THIS LARGE ARRAY OF POTENTIAL ENGINES, THREE CANDIDATE SYSTEMS WERE SELECTED. TWO OF THESE SYSTEMS EMPLOY SINGLE SHAFT ENGINES, ONE WITH A RECUPERATOR AND THE OTHER WITH A ROTARY REGENERATOR. BOTH HAVE VARIABLE INLET GUIDE VANES AND ARE COUPLED TO INFINITELY VARIABLE SPEED RATIO TRACTION TRANSMISSIONS. THE THIRD CANDIDATE SYSTEM IS A REGENERATED, VARIABLE GEOMETRY FREE-TURBINE ENGINE COUPLED TO A THREE-SPEED AUTOMATIC TRANSMISSION.

FIGURE 1 PRESENTS A SCHEMATIC OF THE TWO SINGLE-SHAFT SYSTEMS. THESE ENGINES FEATURE CONTINUOUSLY VARIABLE INLET GUIDE VANES, A SINGLE-STAGE CENTRIFUGAL COMPRESSOR, AND A SINGLE-STAGE RADIAL INFLOW TURBINE. OUTPUT POWER IS EXTRACTED FROM THE COMPRESSOR END OF THESE ENGINES. A TWO-STAGE GEAR TRAIN REDUCES ENGINE SPEED TO A LEVEL ACCEPTABLE TO THE VARIABLE SPEED DRIVE. THE ON-OFF CLUTCH IS ONLY DISENGAGED DURING ENGINE START-UP TO FACILITATE ADEQUATE OIL PRESSURE BUILD-UP PRIOR TO START OF TRACTION-DRIVE OUTPUT SHAFT ROTATION. THE TRANSMISSION OUTPUT SHAFT DRIVES A CONVENTIONAL TORQUE CONVERTER COUPLED TO A FORWARD AND REVERSE GEARBOX.



*WHERE TWO NUMBERS ARE GIVEN, THE FIRST APPLIES TO THE RECUPERATED CYCLE AND THE SECOND TO THE REGENERATED CYCLE

FIGURE 1

THE FREE-TURBINE POWERED CANDIDATE SYSTEM IS SHOWN IN FIGURE 2. THIS ENGINE USES VARIABLE INLET GUIDE VANES AND VARIABLE POWER TURBINE NOZZLES; BOTH CONTINUOUSLY VARIABLE. THE GAS GENERATOR SECTION HAS A SINGLE-STAGE CENTRIFUGAL COMPRESSOR AND A SINGLE-STAGE RADIAL TURBINE. THE POWER TURBINE CONSISTS OF A SINGLE-STAGE AXIAL COMPONENT. IN THIS ENGINE CONFIGURATION, OUTPUT POWER IS EXTRACTED FROM THE POWER TURBINE AT THE TURBINE END OF THE ENGINE. A CONVENTIONAL 3-SPEED AUTOMATIC TRANSMISSION, WITH A SLIGHTLY MODIFIED GEAR RATIO, IS COUPLED TO THE ENGINE WITHOUT A TORQUE CONVERTER.

FREE-TURBINE ENGINE - SYSTEM SCHEMATIC

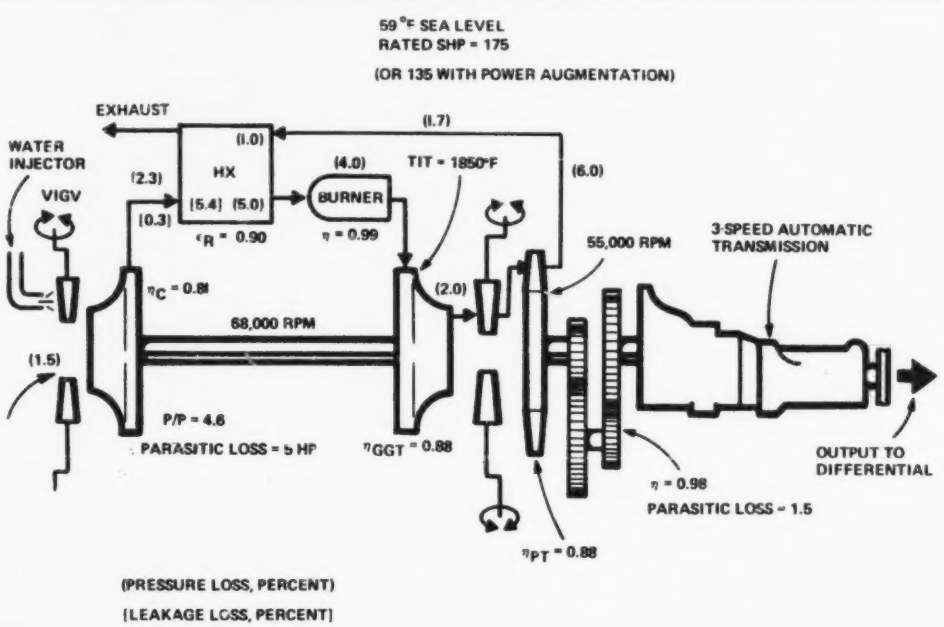


FIGURE 2

TABLE 1 PRESENTS THE DESIGN CHARACTERISTICS OF THE THREE CANDIDATE SYSTEMS FOR THE POWER-AUGMENTED VERSIONS OF THE ENGINES. FOR THE NON-POWER-AUGMENTED ENGINES, THE AIRFLOW IS

TABLE 1

CANDIDATE ENGINE DESIGN POINT CHARACTERISTICS
(59°F SEA-LEVEL RATING)

CYCLE	1	2	3
PARAMETER	FREE-TURBINE REGENERATED	SINGLE-SHAFT, RECUPERATED	SINGLE-SHAFT, REGENERATED
AIRFLOW, LB/SEC	1.63	1.21	1.22
PRESSURE RATIO	4.8	6.4	4.6
COMPRESSOR EFFICIENCY	0.81	0.79	0.82
COMPRESSOR SPEED, RPM	77,000	83,600	84,100
COMBUSTOR EFFICIENCY	0.99	0.99	0.99
TURBINE INLET TEMP., °F	1850	1900	1900
COMPRESSOR TURBINE EFFICIENCY	0.88	0.88	0.88
FREE-TURBINE EFFICIENCY	0.88	---	---
FREE-TURBINE SPEED, RPM	62,900	---	---
HEAT RECOVERY EFFECTIVENESS	0.90	0.85	0.90
OUTPUT POWER, SHP	135	125	108
SFC, $\frac{LB}{HP\,HR}$	0.43	0.41	0.42

INCREASED BY THE RATIO OF OUTPUT POWERS, AND THE SHAFT SPEEDS ARE DECREASED BY THE INVERSE RATIO OF OUTPUT POWERS TO THE 0.5 POWER. ALL OTHER FACTORS OF THIS TABLE REMAIN THE SAME FOR CHANGES IN THE POWER RATING.

FIGURE 3 SHOWS STANDING-START ACCELERATION PERFORMANCE (FOR THE FIRST 150 FT) OF THE CANDIDATE GT SYSTEMS COMPARED TO A 350-IN.^{3} V-8 SI ENGINE. PROPER DESIGN OF THE GT SYSTEMS ENSURES THAT ESSENTIALLY NO ACCELERATION LAG WILL EXIST RELATIVE TO THE CONVENTIONAL VEHICLE.

STANDING START ACCELERATION PERFORMANCE OF CANDIDATE SYSTEMS

AMBIENT CONDITIONS: 105°F, SEA LEVEL
VEHICLE WEIGHT = 4000 LB FOR TURBINES
4300 LB FOR SPARK IGNITION

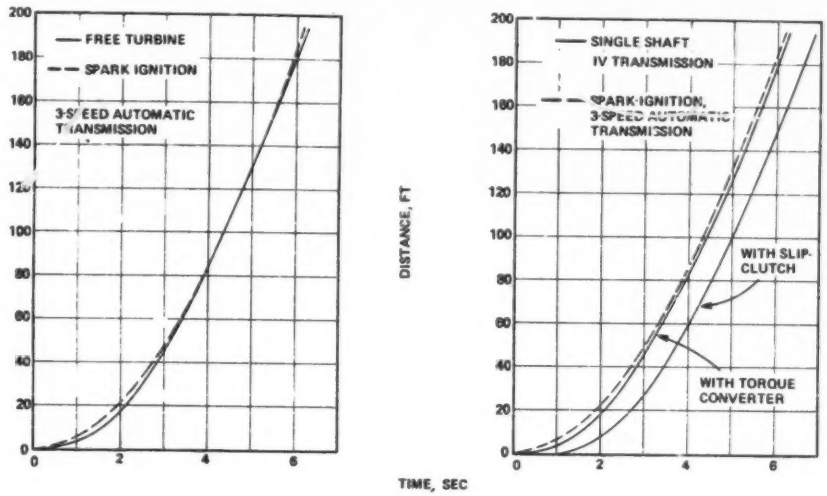


FIGURE 3

TABLE 2 SHOWS A COMPARISON OF ACCELERATION PERFORMANCE FOR THE THREE CANDIDATE SYSTEMS ON THE SPECIFIED 105°F DAY. THE POWER RATING OF EACH ENGINE WAS SELECTED TO ENSURE THAT ALL PERFORMANCE REQUIREMENTS ARE SATISFIED.

TABLE 2

VEHICLE ACCELERATION PERFORMANCE (4000-LB AUTOMOBILE, 105°F, SEA-LEVEL)

ENGINE	0–440 FT, SEC	0–60 MPH, SEC	25–70 MPH, SEC	DOT PASS, SEC
SINGLE-SHAFT REGENERATED	10.0	12.8	15.0	15.0
SINGLE-SHAFT RECUPERATED	10.5	12.2	13.6	14.9
FREE-TURBINE REGENERATED	9.8	11.9	14.6	15.5
EPA REQUIREMENT	10.5	14.3	15.8	15.8

THE FUEL ECONOMY STUDY RESULTS FOR SEVERAL FREE-TURBINE SYSTEMS, COMPARED TO 1970 SI SYSTEMS, ARE PRESENTED IN TABLE 3. THE FEDERAL DRIVING CYCLE AND THE COMPOSITE ROUTE WERE USED AS THE BASIS FOR THESE CALCULATIONS. THE FREE-TURBINE SYSTEM ACHIEVES BETTER FUEL ECONOMY

TABLE 3

FUEL ECONOMY COMPARISONS (85°F SEA-LEVEL)

ENGINE	60°F SEA LEVEL RATED, SHP	TRANSMISSION	VEHICLE WEIGHT, LB	FDC, MPG	COMPOSITE ROUTE, MPG
FREE-TURBINE, REGEN (0.90)	175	3-SPD AUTO	4,000	16.4	19.9
FREE-TURBINE, REGEN (0.90)	135*	3-SPD AUTO	4,000	18.1	21.6
1970 SPARK-IGNITION	175	3-SPD AUTO	4,300	12.5	14.8
1970 SPARK-IGNITION	175	TRACTION	4,300	14.2	18.0
FREE-TURBINE, REGEN (0.90)	175	TRACTION	4,000	15.8	18.9
FREE-TURBINE, REGEN (0.90)	135*	TRACTION	4,000	17.4	20.5

*30 PERCENT POWER AUGMENTATION USED FOR HOT DAY PERFORMANCE

WITH THE THREE-SPEED TRANSMISSION THAN WITH THE TRACTION DRIVE BECAUSE OF THE GREATER EFFICIENCY OF THE THREE-SPEED AT LOW OUTPUT POWER. THE GAIN REALIZED BY ALLOWING THE FREE-TURBINE TO OPERATE NEAR MINIMUM SFC WITH THE INFINITELY VARIABLE TRANSMISSION IS OVERCOME BY THE LOSS IN TRANSMISSION EFFICIENCY.

TABLE 4 SHOWS THE FUEL ECONOMY STUDY RESULTS FOR THE SINGLE-SHAFT CONFIGURATIONS COMPARED TO THE SI SYSTEMS. ALL BUT ONE OF THE CONFIGURATIONS EMPLOYED A SLIPPING CLUTCH. THE ONE USED A TORQUE CONVERTER, AS NOTED ON THE TABLE. THE TORQUE CONVERTER SYSTEM CONSUMES AN APPROXIMATE AVERAGE OF 1 MPG MORE FUEL THAN THE SLIPPING CLUTCH SYSTEM. HOWEVER, THE TORQUE CONVERTER IS MORE DESIRABLE FOR ACHIEVING STANDING-START ACCELERATION PERFORMANCE AND MINIMIZING SYSTEM COST. A LIMITING CASE IS SHOWN BY THE LAST TWO ITEMS ON THE TABLE, WHERE IT IS ASSUMED THAT THE VEHICLE IS LOADED TO 4600 LB. THE POWER REQUIRED TO MEET THE ACCELERATION PERFORMANCE WAS COMPUTED, THEN THE RESULTING FUEL ECONOMY WAS DETERMINED.

TABLE 4

FUEL ECONOMY COMPARISONS (85°F SEA-LEVEL)

ENGINE	60°F SEA LEVEL RATED, SHP	TRANSMISSION	VEHICLE WEIGHT, LB	FDC, MPG	COMPOSITE ROUTE, MPG
SINGLE-SHAFT RECUP (0.85)	125*	BELT	4000	14.3	20.0
SINGLE-SHAFT REGEN (0.90)	155	BELT	4000	14.0	19.7
SINGLE-SHAFT REGEN (0.90)	108*	BELT	4000	17.0	22.1
1970 SPARK IGNITION	175	3-SPD AUTO	4300	12.5	14.8
1970 SPARK IGNITION	175	TRACTION	4300	14.2	18.0
SINGLE-SHAFT RECUP (0.85)	125*	TRACTION	4000	11.5	17.2
SINGLE-SHAFT REGEN (0.90)	108*	TRACTION	4000	15.8	20.8
SINGLE-SHAFT REGEN (0.90)	155	TRACTION**	4000	13.7	18.5
SINGLE-SHAFT REGEN (0.90)	122*	TRACTION	4600	13.8	18.8
SINGLE-SHAFT REGEN (0.90) (T_4 = 1700°F)	122*	TRACTION	4600	11.7	16.8

*30 PERCENT POWER AUGMENTATION USED FOR HOT-DAY PERFORMANCE
**TORQUE CONVERTER

TABLE 5 PRESENTS A SUMMARY OF THE ESTIMATED MANUFACTURING AND CONSUMER INITIAL COSTS FOR THE AUTOMOBILE, COMPARING FIVE VERSIONS OF THE CANDIDATE GT SYSTEMS WITH THE 1970 SI SYSTEM. THE CONSUMER COST OF THE 1970 SI VEHICLE WAS OBTAINED FROM A DEPARTMENT OF COMMERCE PUBLICATION. THE MANUFACTURING COST ESTIMATES WERE BASED ON AN ASSUMED MANUFACTURING LABOR COST OF $10 PER HOUR AND A PRODUCTION RATE OF ONE MILLION UNITS PER YEAR. THE RESULTS SHOW THAT THE SINGLE-SHAFT SYSTEMS CAN BE PRODUCED AT A COST CONSIDERABLY LOWER THAN THE FREE-TURBINE SYSTEMS, BUT GREATER THAN THE 1970 SI SYSTEM EMPLOYING NO ADDITIONAL EMISSION CONTROL DEVICES.

TABLE 5

ESTIMATED MANUFACTURING AND CONSUMER COST

ENGINE/TRANSMISSION CONFIGURATION	SYSTEM CONTROLS / ENGINE	TRANSMISSION / ACCESSORIES	DRIVE LINE, BODY, FRAME, INTERIOR, WHEELS, TIRES, AND MISC.	TOTAL MANUFACTURING COST	TOTAL CONSUMER COST
V-8 SPARK IGNITION, AUTOMATIC TRANSMISSION	$356	--	$267	$1157	$1780	$ 3185
FREE-TURBINE, REGENERATED, AUTOMATIC TRANSMISSION	820	$161	$81	267	1150	2459	4596
SINGLE-SHAFT, REGENERATED, TRACTION TRANSMISSION	429	137	61	233	1150	2010	3788
SINGLE-SHAFT, REGENERATED, BELT TRANSMISSION	429	137	61	197	1150	1974	3723
SINGLE-SHAFT, RECUPERATED (METAL), BELT TRANSMISSION	526	137	57	197	1150	2067	3890
SINGLE-SHAFT, RECUPERATED (CERAMIC), BELT TRANSMISSION	480	137	57	197	1150	2021	3808

TABLE 6 SHOWS A SUMMARY OF THE ESTIMATED REPAIR AND MAINTENANCE COSTS FOR THE CANDIDATE GT SYSTEMS. THESE COSTS INCLUDE ITEMS APPLICABLE ONLY TO A GAS TURBINE ENGINE, SUCH AS

TABLE 6

REPAIR AND MAINTENANCE ESTIMATED FOR 105,000 MILES, 7-YEAR LIFE, GAS TURBINE ENGINES

ENGINE/TRANSMISSION SYSTEM	FIRST YEAR	THIRD YEAR	SEVENTH YEAR	SEVEN YEAR TOTAL
(1) SINGLE-SHAFT, REGENERATED, TRACTION TRANSMISSION	$57.50	$109.00	$74.00	$801.50
(2) SINGLE-SHAFT, REGENERATED, BELT TRANSMISSION	57.50	109.00	86.50	851.50
(3) SINGLE-SHAFT, RECUPERATED, BELT TRANSMISSION	57.50	100.00	86.50	824.00
(4) FREE-TURBINE, REGENERATED, THREE-SPEED AUTOMATIC TRANSMISSION	57.50	104.00	100.00	891.00

REPLACEMENT OF THE IGNITION COIL, LEAD AND IGNITION; INSPECTION OF THE COMBUSTOR LINER; AND REPLACEMENT OF REGULATOR SEALS WHERE APPLICABLE. OTHER ITEMS INCLUDED ARE COMMON TO BOTH GT- AND SI-POWERED VEHICLES, SUCH AS REPLACEMENT OF THE AIR FILTER, CHASSIS LUBRICATION, FRONT END ALIGNMENT, RELINING BRAKES, REPLACEMENT OF STARTER BRUSHES, REPLACEMENT OF THE ALTERNATOR, AND OTHER SMALLER ITEMS. THE REPAIR AND MAINTENANCE COST ESTIMATE FOR THE SI ENGINE (AS REPORTED BY THE DEPARTMENT OF COMMERCE) IS SLIGHTLY OVER $1500, OR MORE THAN $600 HIGHER THAN THE COST FOR THE GT ENGINES. THE MAJOR PART OF THIS DIFFERENCE IS FOUND IN THE ENGINE OVERHAUL COST ($250) AND OIL CHANGES ($150) OVER THE LIFE OF THE PISTON ENGINE. THE GAS TURBINE CAN BE DESIGNED FOR A LIFE EXCEEDING 3500 HR, THEREFORE, ENGINE OVERHAUL WOULD NOT BE REQUIRED. THE TURBINES ARE ALSO DESIGNED TO RUN ON FOIL-TYPE AIR BEARINGS, THEREBY ELIMINATING THE REQUIREMENT FOR OIL CHANGES.

COST-OF-OWNERSHIP COMPARISONS FOR THE CANDIDATE SYSTEMS AND THE SI SYSTEM FOR THE SPECIFIED 7-YEAR, 105,000-MILE LIFE OF THE VEHICLE ARE SHOWN IN TABLE 7. THE RESULTS SHOW THAT ALL OF THE GT-POWERED VEHICLES HAVE ESTIMATED COSTS-OF-OWNERSHIP LOWER THAN THAT OF A 1970 AUTOMOBILE USING A CONVENTIONAL ENGINE. OF THE GT SYSTEMS, THE SINGLE-SHAFT VERSIONS HAVE THE

TABLE 7

COST-OF-OWNERSHIP COMPARISONS

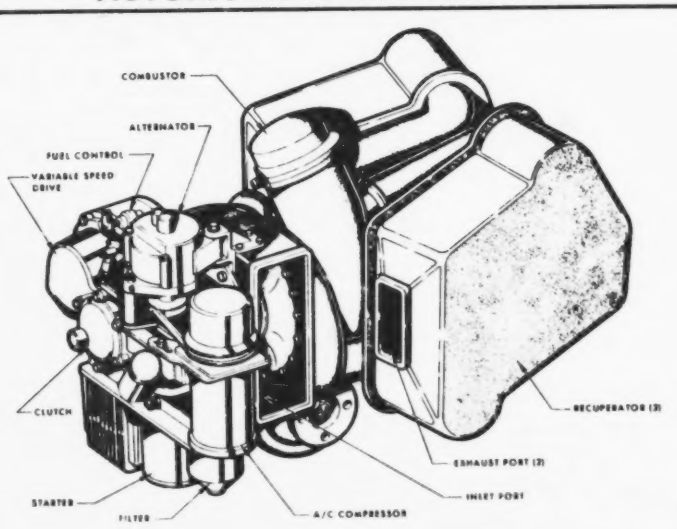
SYSTEM	DEPRECIATION	REPAIRS AND MAINTENANCE	FUEL AND WATER COST	OIL	OTHER*	TOTAL COST OF OWNERSHIP	COST OF OWNERSHIP, PERCENT
V8 SPARK-IGNITION, AUTOMATIC TRANSMISSION	$3105	$1522	$2560	$158	$4469	$11,894	100
FREE-TURBINE, REGENERATED, AUTOMATIC TRANSMISSION	4595	891	1700	--	4469	11,655	98
SINGLE-SHAFT, REGENERATED TRACTION TRANSMISSION	3788	802	1773	--	4469	10,832	91
SINGLE-SHAFT, REGENERATED, BELT TRANSMISSION	3723	851	1670	--	4469	10,711	90
SINGLE-SHAFT, RECUPERATED (METAL) BELT TRANSMISSION	3890	824	1842	--	4469	11,025	93
SINGLE-SHAFT, RECUPERATED (CERAMIC), BELT TRANSMISSION	3808	824	1842	--	4469	10,943	92

*INCLUDES TIRES, INSURANCE, TAXES, GARAGING, PARKING, TOLLS.

LOWEST INITIAL COST, LOWEST MAINTENANCE AND REPAIR COSTS, AND THE LOWEST TOTAL COST OF OWNERSHIP. THEREFORE, A SINGLE-SHAFT ENGINE WITH HIGH HEAT RECOVERY EFFECTIVENESS AND VARIABLE COMPRESSOR GEOMETRY, DRIVING THE VEHICLE THROUGH AN INFINITELY VARIABLE TRACTION TRANSMISSION, IS RECOMMENDED AS THE MOST PROMISING GT SYSTEM FOR THE AUTOMOBILE. IT IS SHOWN THAT THIS SYSTEM SATISFIES THE COST, PERFORMANCE, AND FUEL ECONOMY OBJECTIVE OF THE PROGRAM. TO FURTHER ENHANCE THIS SELECTION, AIRESEARCH IS RAPIDLY PROGRESSING TOWARD A COMBUSTOR DESIGN THAT WILL MEET THE 1976 FEDERAL EMISSIONS STANDARDS.

A PICTORIAL PRESENTATION OF A RECUPERATED VERSION OF THE RECOMMENDED SINGLE-SHAFT ENGINE SYSTEM IS SHOWN BY FIGURE 4. THIS DESIGN FEATURES A DUAL-MODULE RECUPERATOR WITH

ADVANCED GAS TURBINE AUTOMOBILE DEMONSTRATOR



SINGLE ROTOR, FOIL BEARINGS
VARIABLE COMPRESSOR IGV'S
WASTE HEAT RECOVERY
VARIABLE SPEED DRIVE

→ DEMONSTRATION PROGRAM
- EPA EMISSION GOALS
- LOW FUEL CONSUMPTION
- RAPID RESPONSE/ACCELERATION

→ LONG RANGE POTENTIAL
- LOW INITIAL COST
- LOW COST OF OWNERSHIP
- HIGH RELIABILITY

FIGURE 4

DESIGN POINT EFFECTIVENESS OF 0.85, INTEGRATION OF VEHICLE AND ENGINE ACCESSORIES, AN INFINITELY VARIABLE TRANSMISSION, AND AN INTEGRATED DIFFERENTIAL.

A MOCK-UP PHOTOGRAPH OF A 150 HP SINGLE-SHAFT ENGINE/TRANSMISSION SYSTEM IS SHOWN BY FIGURE 5. THE MOCK-UP SHOWN IS FOR INSTALLATION AS A REAR-ENGINE REAR-DRIVE SYSTEM, BUT THE UNIT IS READILY ADAPTABLE TO FRONT INSTALLATION WITH EITHER FRONT- OR REAR-WHEEL DRIVE.

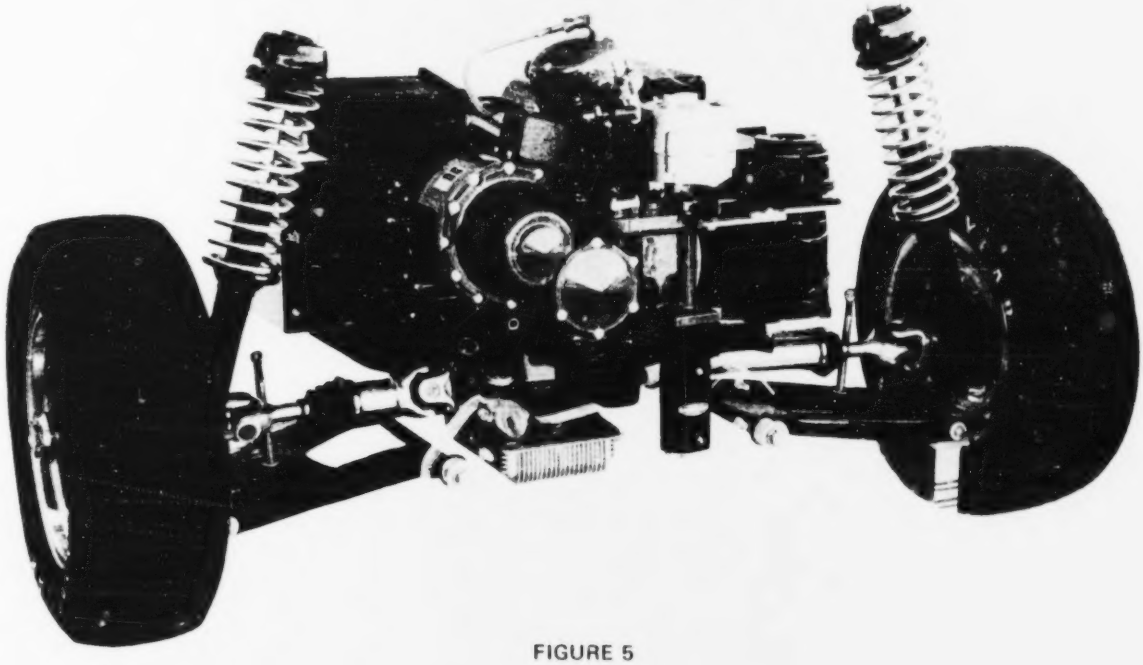


FIGURE 5

THE DIMENSIONS OF THIS ENGINE/TRANSMISSION PACKAGE ARE:

- 39 IN. LONG
- 30 IN. WIDE
- 27 IN. HIGH

FOR A FRONT ENGINE REAR DRIVE INSTALLATION, THE SYSTEM WEIGHT IS APPROXIMATELY 300 LB LESS THAN THE SYSTEM WITH A 350 IN.^{3} V-8 ENGINE AND AN AUTOMATIC TRANSMISSION.

FIGURE 6 SHOWS A CONDENSED VERSION OF THE STEPS INVOLVED IN ACHIEVING VEHICLE-DEMONSTRATION OF THE RECOMMENDED GT SYSTEM.

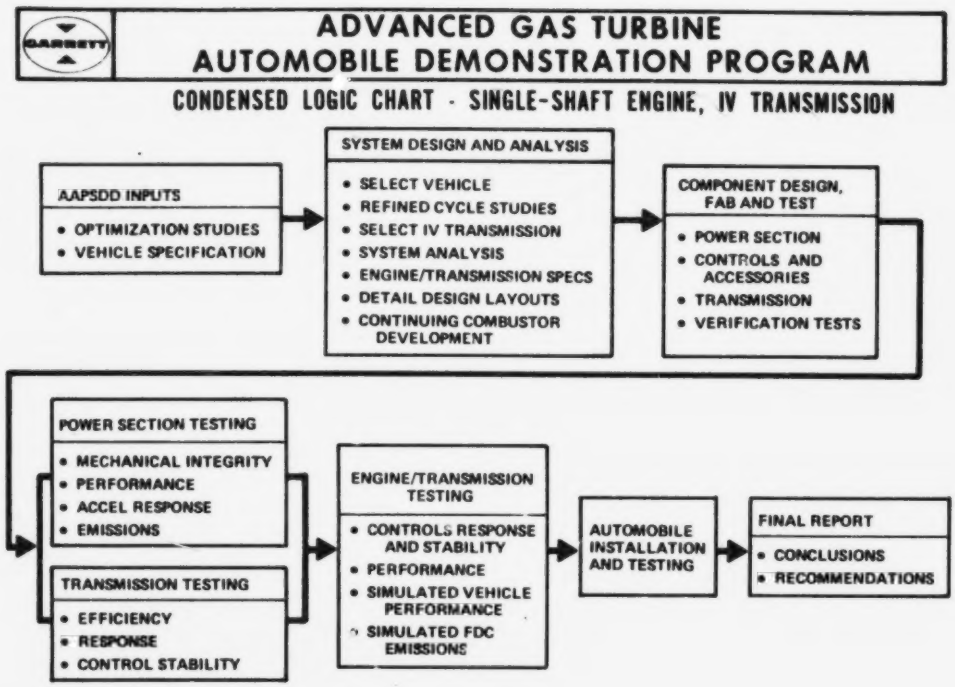


FIGURE 6

THE RESULTS OF THE ENGINE, COMBUSTOR, AND TRANSMISSION STUDIES WILL BE USED TO DEFINE DETAILS OF THE SYSTEM. A VEHICLE WOULD BE SELECTED EARLY IN THE PROGRAM TO DEFINE THE ENVELOPE DIMENSIONS OF THE ENGINE COMPARTMENT, TO SPECIFY THE ENGINE-MOUNTING POINTS, AND TO DESIGN INLET AND EXHAUST SYSTEM LOCATIONS.

REFINED CYCLE STUDIES WOULD BE PERFORMED, IF REQUIRED, TO ACCOUNT FOR MODIFICATIONS IN THE SYSTEM, SUCH AS INCREASED PRESSURE DROP FOR THE LOW-EMISSION COMBUSTOR OR LIMITATIONS ON THE COMBUSTOR INLET TEMPERATURE. MISSION ANALYSIS STUDIES WOULD BE PERFORMED TO MAKE A FINAL SELECTION OF ENGINE POWER RATING TO MEET THE VEHICLE ACCELERATION REQUIREMENTS, TO COMPUTE FUEL ECONOMY, AND TO ESTIMATE FEDERAL DRIVING CYCLE EMISSIONS.

ENGINE AND TRANSMISSION SPECIFICATIONS WOULD BE WRITTEN TO AID IN THE DETAIL DESIGN OF THE SYSTEM COMPONENTS.

NEXT, THE ENGINE, TRANSMISSION, AND CONTROL SYSTEM COMPONENTS WOULD BE DESIGNED IN DETAIL, BUILT, AND TESTED TO VERIFY MECHANICAL AND AERODYNAMIC DESIGN OBJECTIVES. THE ENGINE AND TRANSMISSION WOULD THEN BE TESTED SEPARATELY FOR MECHANICAL INTEGRITY, PERFORMANCE, RESPONSE AND CONTROL STABILITY. EMISSIONS TESTS WOULD ALSO BE RUN ON THE ENGINE.

NEXT, THE TRANSMISSION WOULD BE MATED WITH THE ENGINE FOR DYNAMOMETER TESTING THE COMPLETE SYSTEM. SIMULATED VEHICLE PERFORMANCE, CONTROLS, AND EMISSIONS TESTS WOULD BE CONDUCTED. THE SYSTEM WOULD THEN BE INSTALLED IN THE AUTOMOBILE FOR DEMONSTRATION AND FINAL VERIFICATION TESTS. A FINAL REPORT ON THE RESULTS AND CONCLUSIONS OF THE PROGRAM WOULD BE ISSUED.

A CONDENSED SCHEDULE FOR THE DEMONSTRATION PROGRAM IS SHOWN IN FIGURE 7. A THREE-PHASE PROGRAM IS PROPOSED FOR ACHIEVING SUCCESSFUL DEMONSTRATION OF THE RECOMMENDED GAS TURBINE AUTOMOBILE IN 33 MONTHS.

ADVANCED GAS TURBINE AUTOMOBILE DEMONSTRATION PROGRAM SCHEDULE

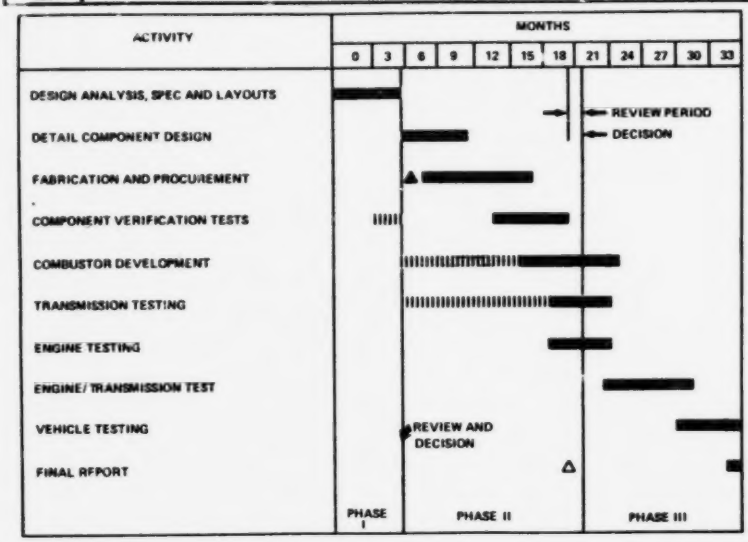


FIGURE 7

PHASE I WOULD CONSIST OF FINAL CYCLE STUDIES, PRELIMINARY DESIGN LAYOUTS OF THE SYSTEM, AND INITIAL TESTING AND DEMONSTRATION OF AN ADVANCED LOW-EMISSION COMBUSTOR, A LOW-COST FUEL CONTROL CONCEPT, AND AN IV TRANSMISSION. THIS PHASE WOULD INCLUDE DETAIL DESIGN OF THE SYSTEM COMPONENTS, COMPONENT VERIFICATION TESTS, AND ENGINE AND TRANSMISSION SUBSYSTEM TESTS. THIS PHASE WOULD REQUIRE 16 MONTHS FOR COMPLETION. IN PHASE III THE ENGINE/TRANSMISSION SYSTEM TESTS WOULD BE COMPLETED, FIRST AS DYNOMOMETER TESTS AND THEN AS VEHICLE TESTS. THIRTEEN MONTHS WOULD BE REQUIRED TO COMPLETE THE PHASE III EFFORT. THE COMPLETE PROGRAM WOULD REQUIRE A TOTAL OF 33 MONTHS.

SIGNIFICANT MILESTONES FOR THE PROGRAM ARE SHOWN IN FIGURE 8. COMPREHENSIVE REVIEWS WOULD BE HELD AT THE END OF EACH PHASE OF THE PROGRAM. THESE REVIEWS COULD BE USED AS DECISION MILESTONES FOR GO-AHEAD ON THE NEXT PHASE OF THE PROGRAM.

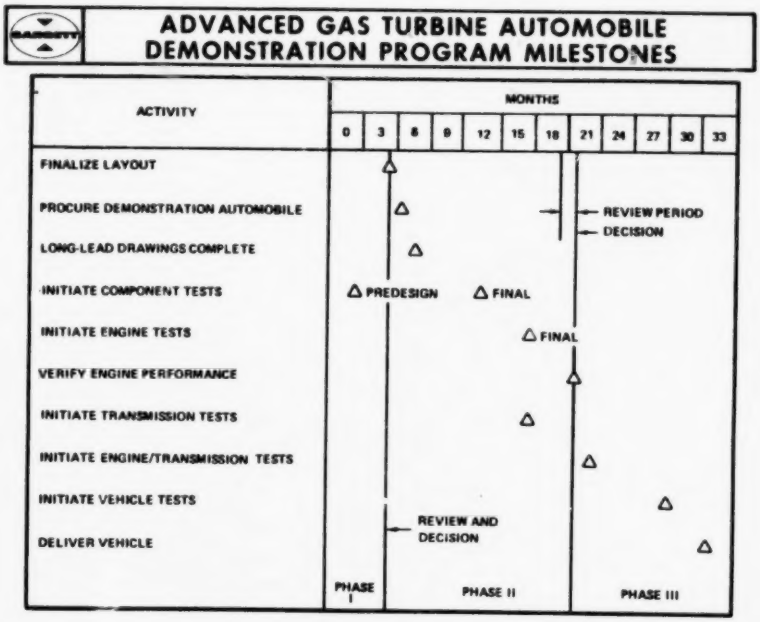


FIGURE 8